



US009231462B2

(12) **United States Patent**
Hunter et al.

(10) **Patent No.:** **US 9,231,462 B2**
(45) **Date of Patent:** **Jan. 5, 2016**

(54) **MINIMIZATION OF TORQUE RIPPLE**

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(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 661 days.

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(21) Appl. No.: **13/587,467**

(22) Filed: **Aug. 16, 2012**

(65) **Prior Publication Data**

US 2013/0093265 A1 Apr. 18, 2013

International Search Report and Written Opinion issued by the Euro-
pean Patent Office as the International Searching Authority in corre-
sponding International Application No. PCT/US12/51131, mailed
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Related U.S. Application Data

(60) Provisional application No. 61/524,089, filed on Aug.
16, 2011.

(51) **Int. Cl.**
H02K 57/00 (2006.01)
H02K 99/00 (2014.01)
(Continued)

(52) **U.S. Cl.**
CPC **H02K 57/006** (2013.01); **H02K 7/075**
(2013.01); **H02K 41/0356** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H02K 7/14; H02K 7/075; H02K 41/0356;
H02K 57/006
USPC 310/12.15, 20, 22-24, 30, 33-35, 38,
310/80; 290/1 R; 318/400.23, 686, 687
IPC H02K 57/00
See application file for complete search history.

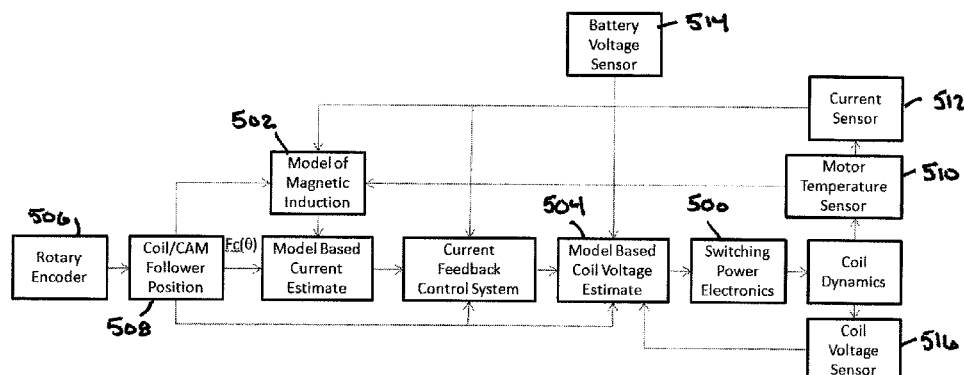
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Hale and Dorr LLP

(57) **ABSTRACT**

An electric motor including: a first and second linear actuator, each linear actuator including a first and second coil respectively, a rotational shaft, a cam assembly mounted on the rotational shaft for translating linear movement of the two linear actuators to rotational movement of the rotational shaft, a controller programmed to generate during operation a first and second drive signal for first coil and second coil respectively, wherein the first drive signal causes the first linear actuator to generate a first torque on the rotational shaft that varies periodically over a complete rotation of the shaft and the second drive signal causes the second linear actuator to generate a second torque on the rotational shaft that varies periodically over a complete rotation of the shaft, and wherein the sum of the first and second torques produces a total torque that is substantially constant throughout the complete rotation of the shaft.

14 Claims, 19 Drawing Sheets



- (51) **Int. Cl.**
H02K 41/035 (2006.01)
H02K 7/075 (2006.01)
H02K 7/14 (2006.01)
- (52) **U.S. Cl.**
CPC *B60L 2220/44* (2013.01); *B60L 2240/423*
(2013.01); *B60L 2240/425* (2013.01); *B60L*
2240/429 (2013.01); *B60L 2270/142* (2013.01);
B60L 2270/145 (2013.01); *H02K 7/14*
(2013.01); *Y02T 10/641* (2013.01)
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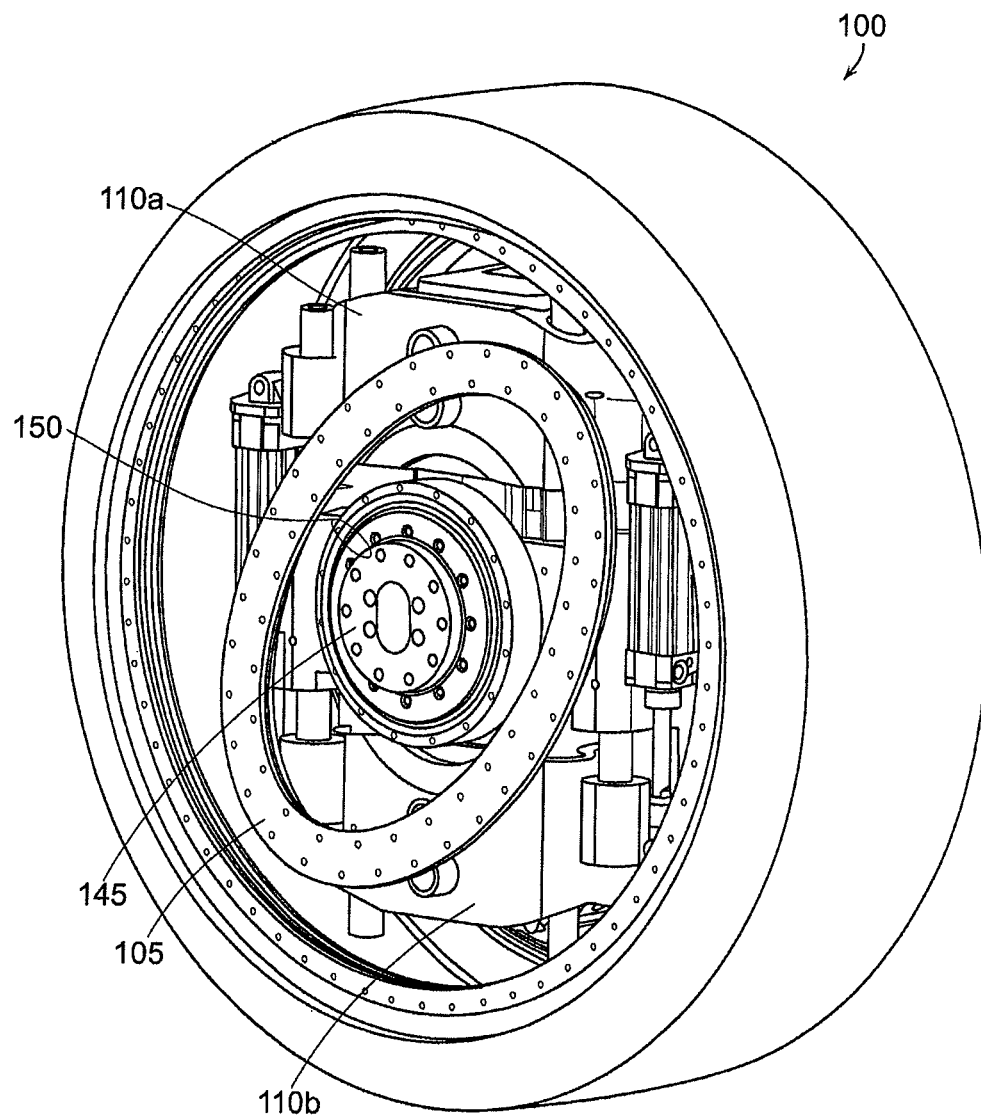


FIG. 1A

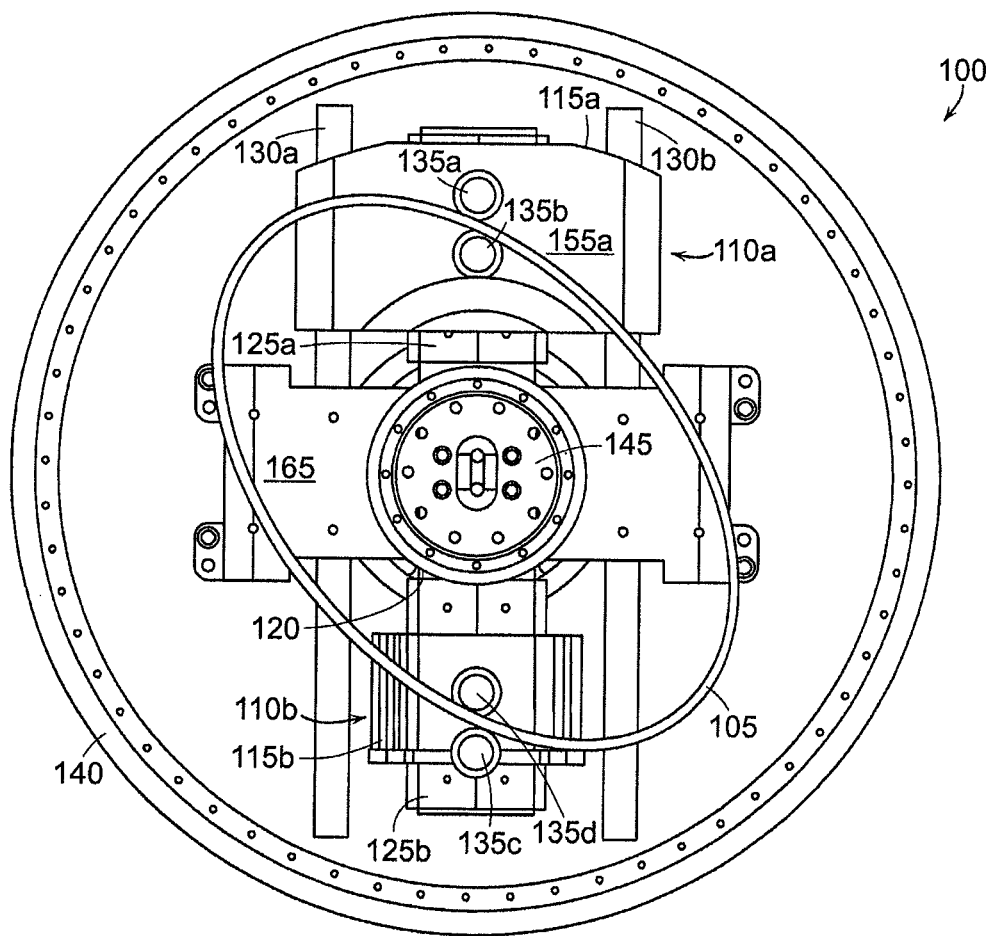


FIG. 1B

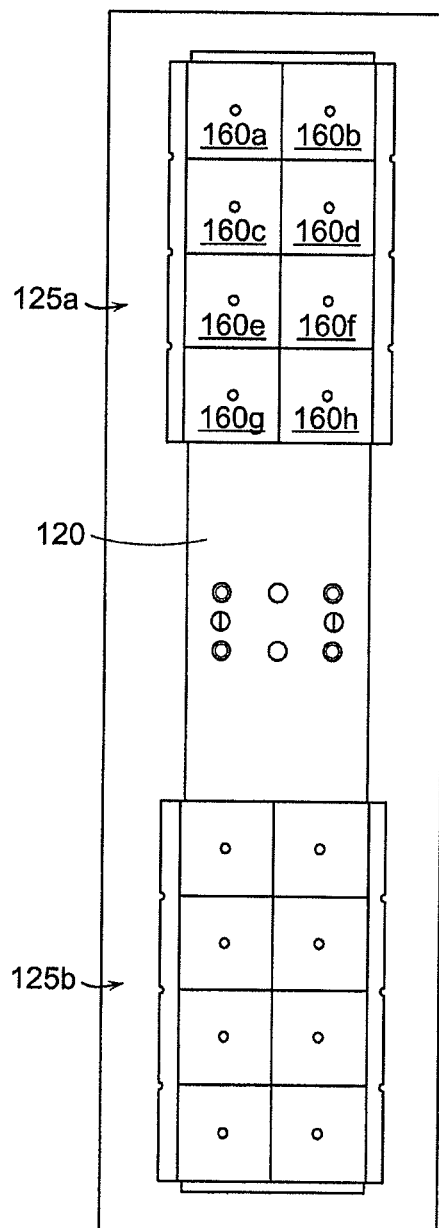


FIG. 1C

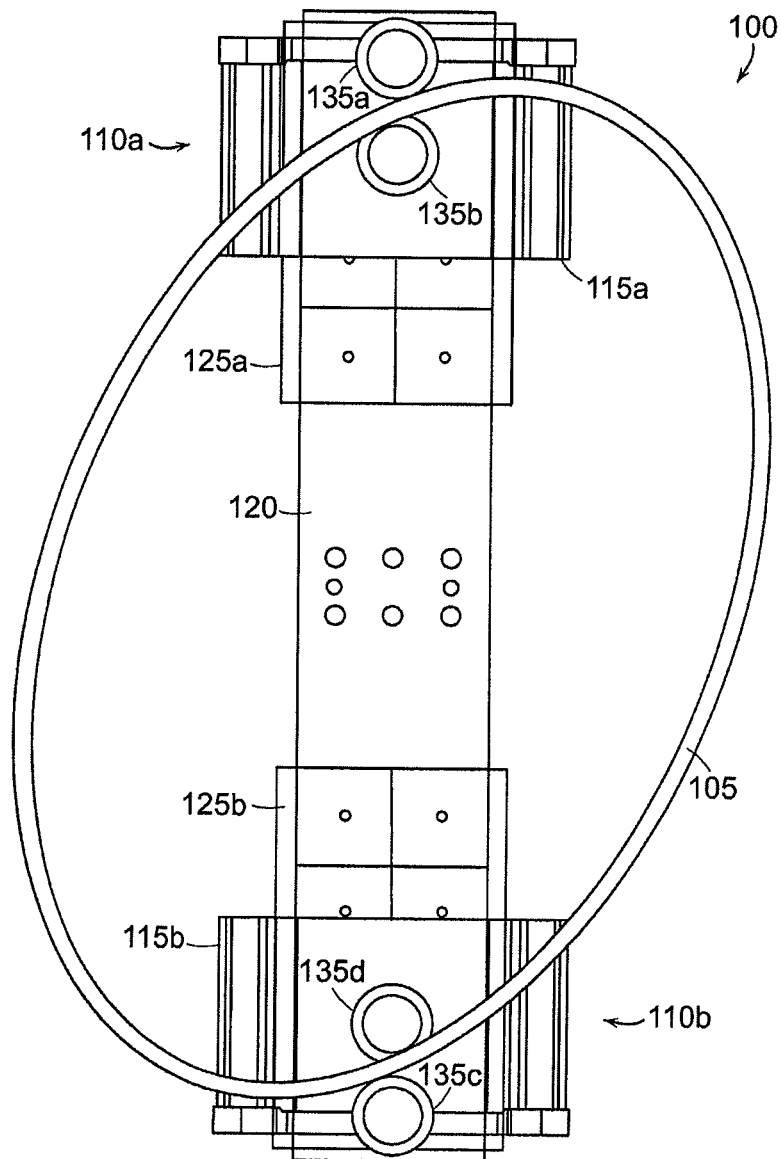


FIG. 2A

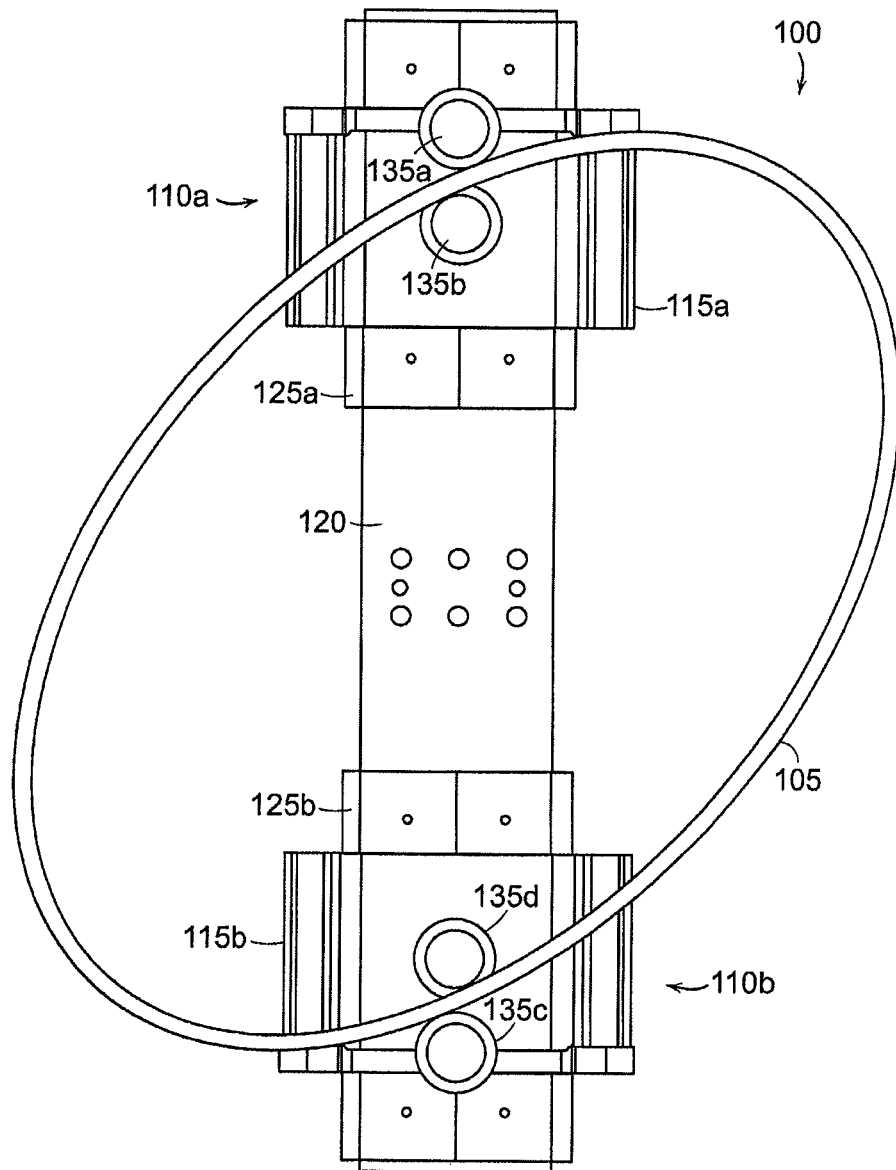


FIG. 2 B

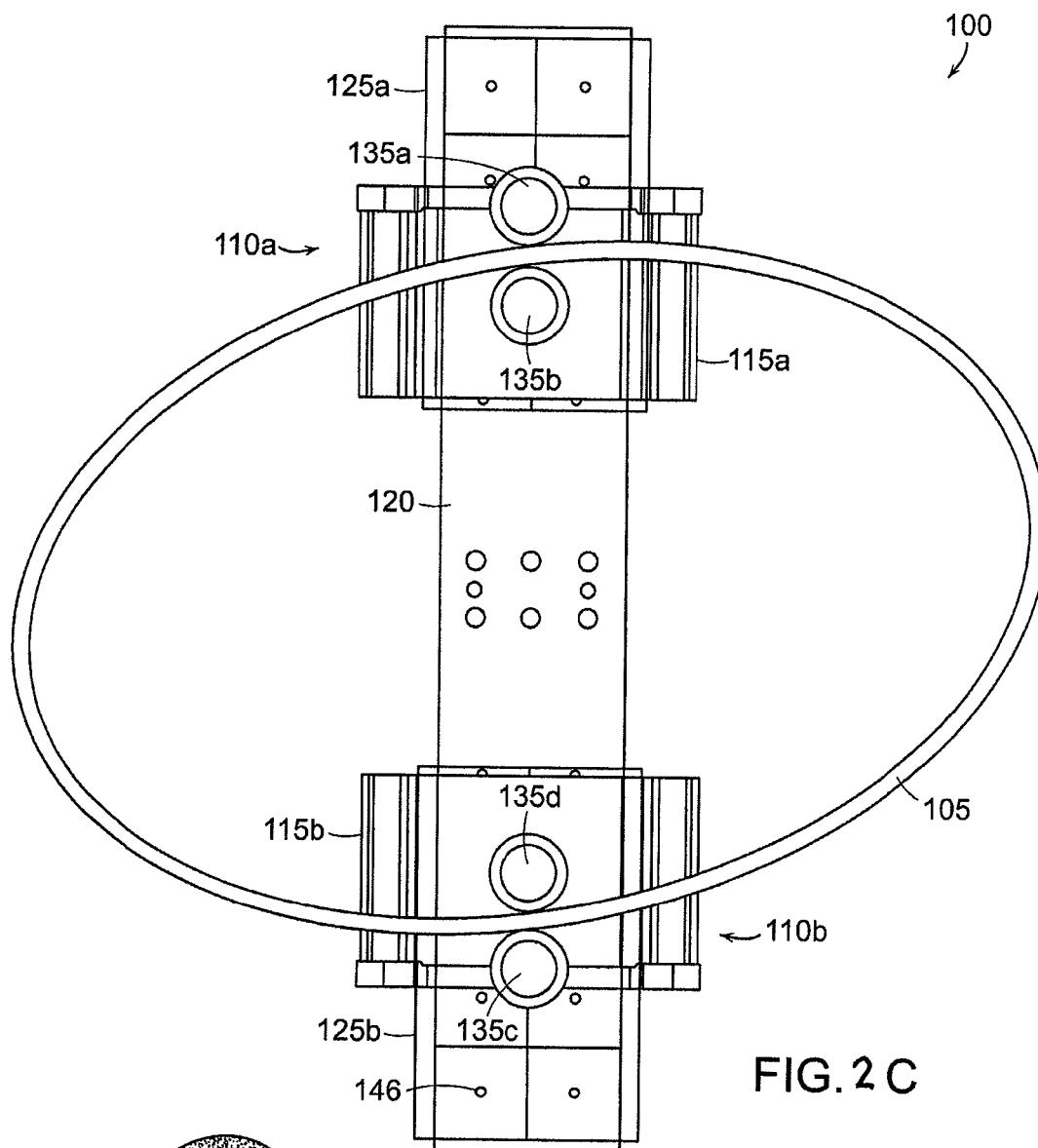


FIG. 2 C

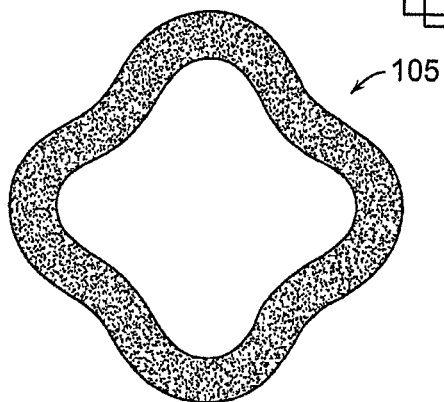


FIG. 2 D

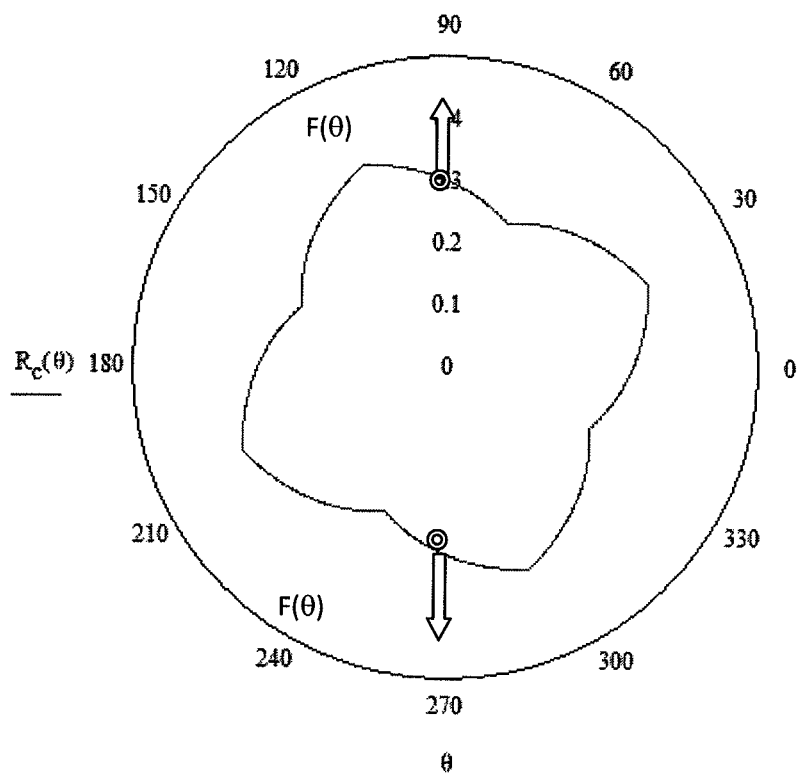


FIG. 3

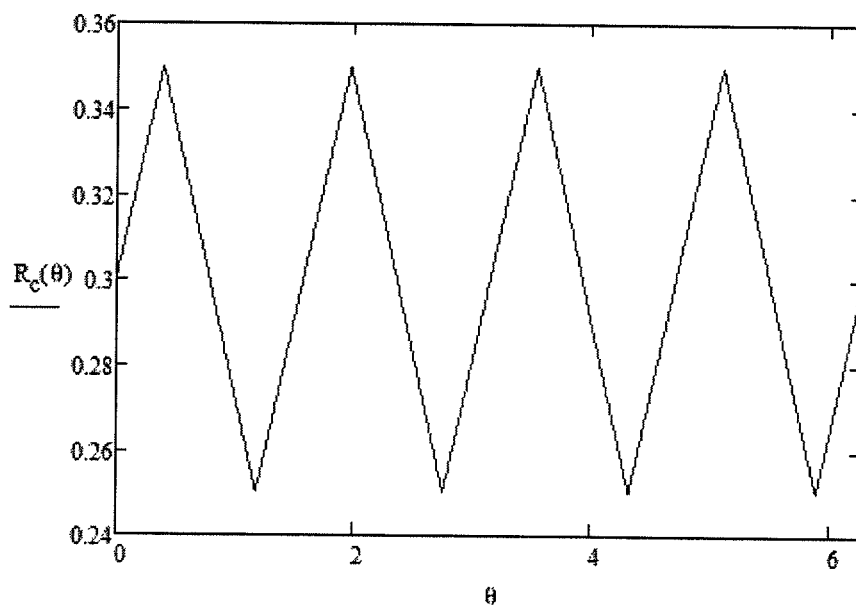


FIG. 4

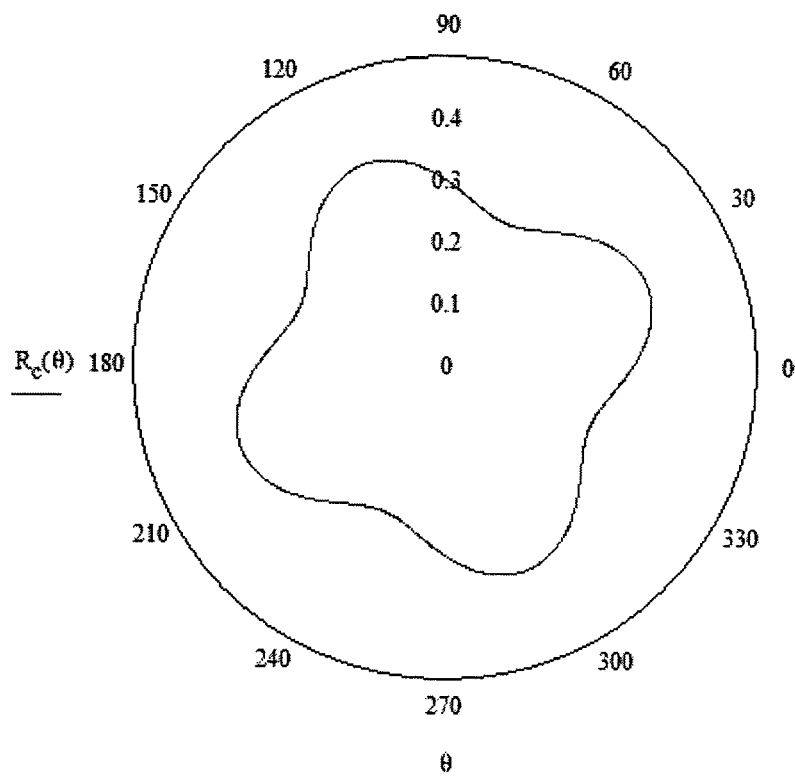


FIG. 5

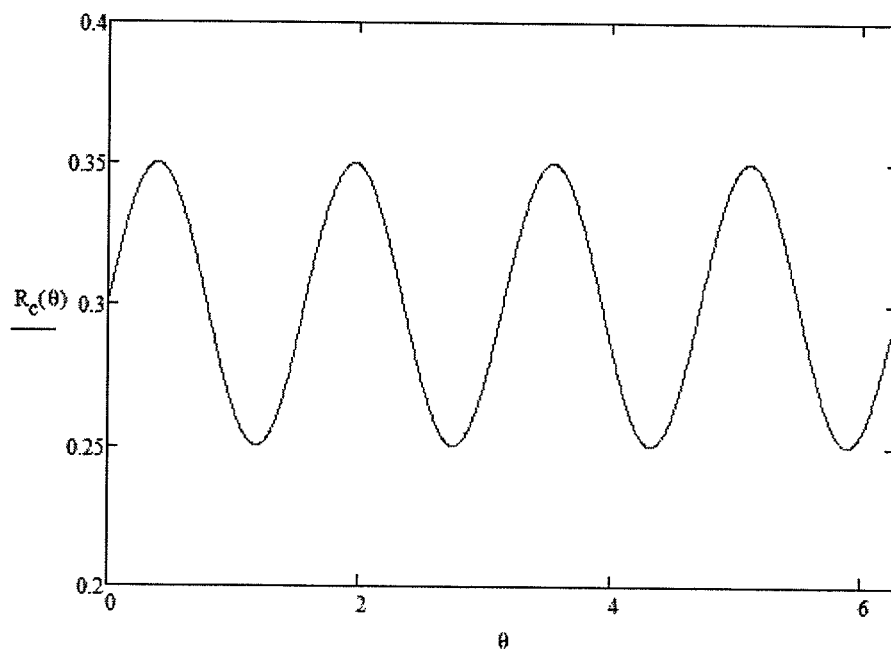


FIG. 6

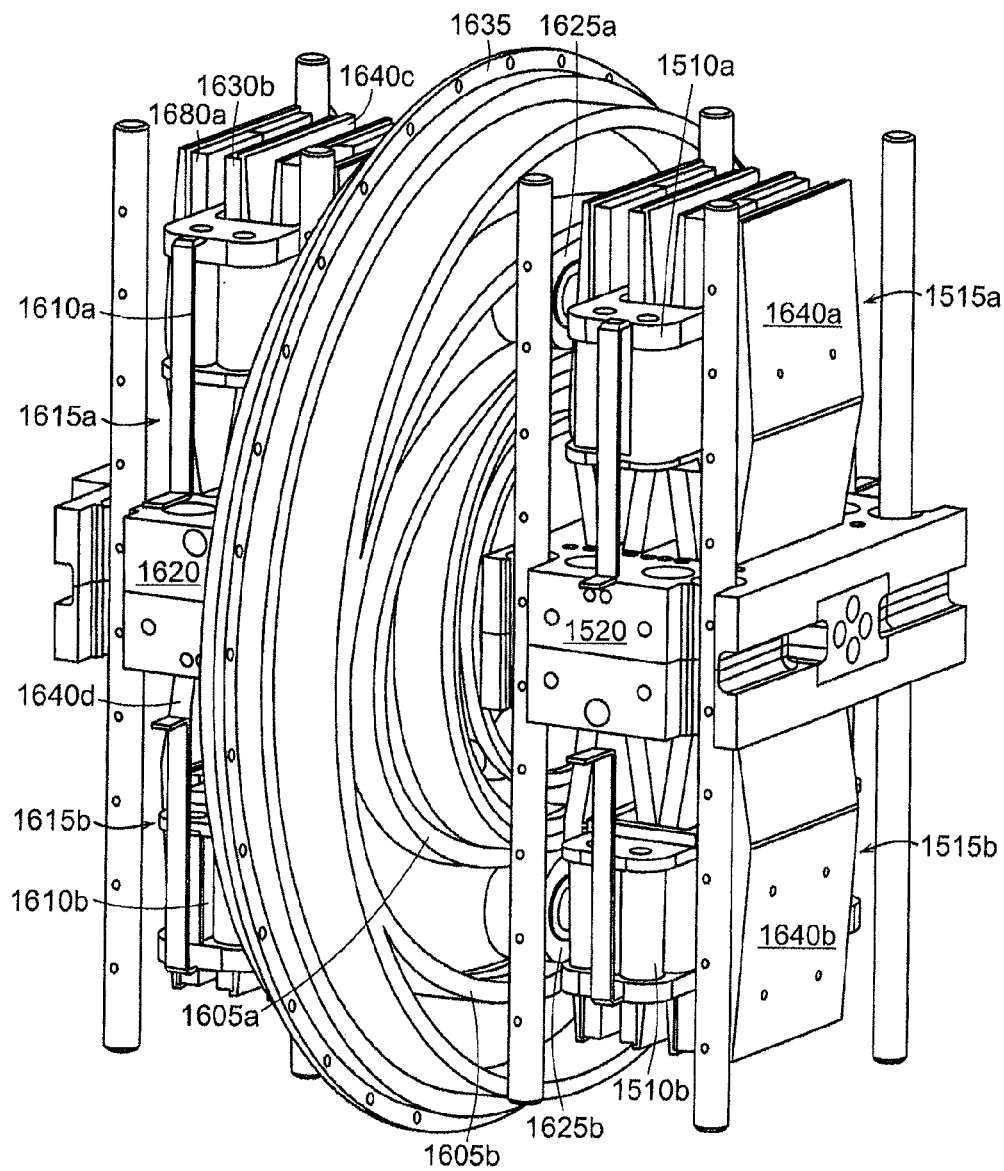


FIG. 7A

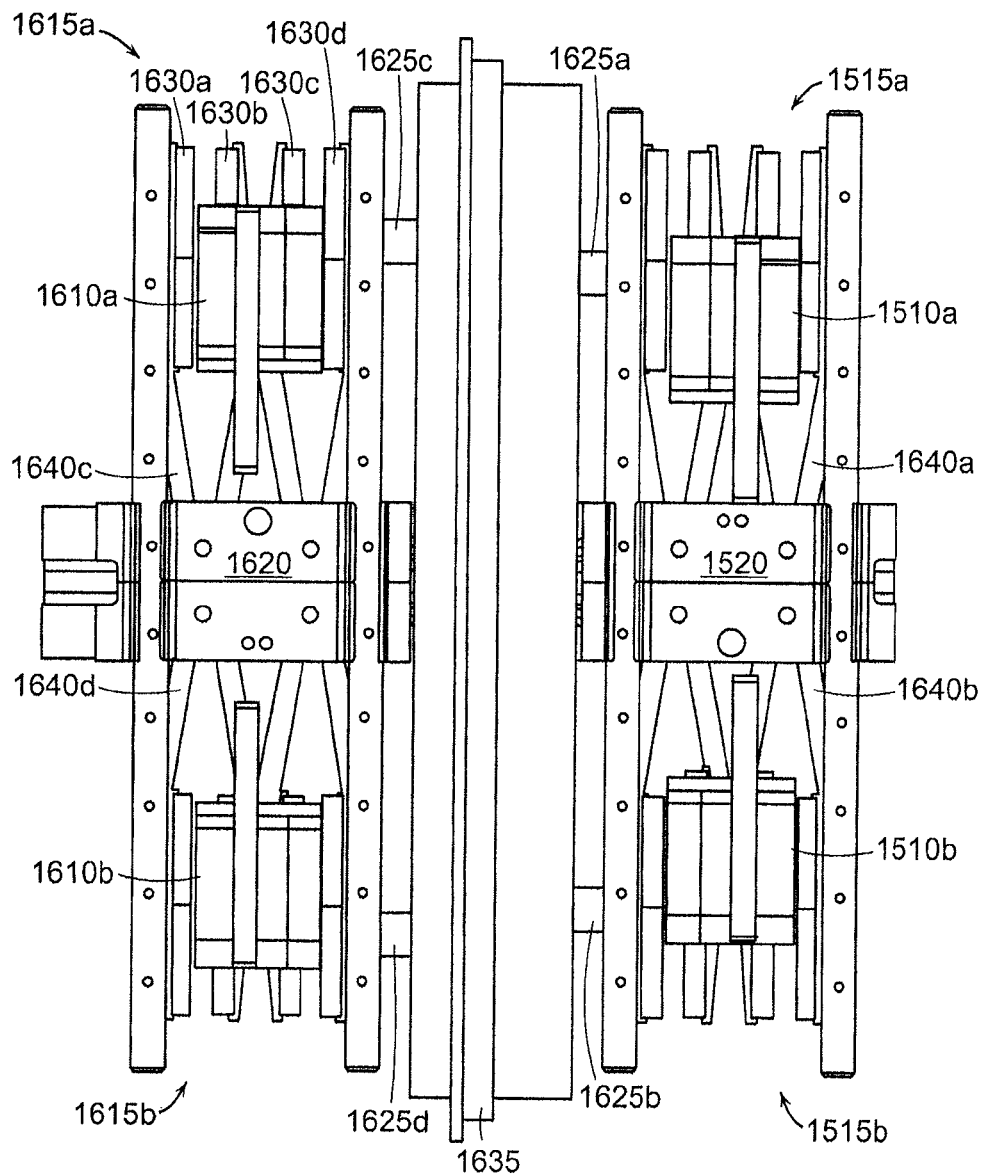


FIG. 7 B

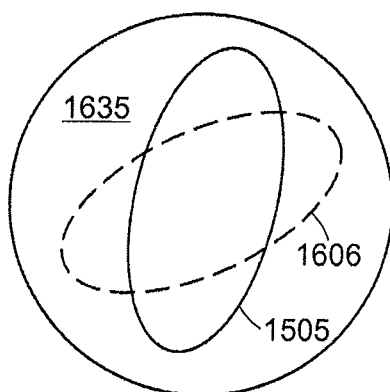


FIG. 8A

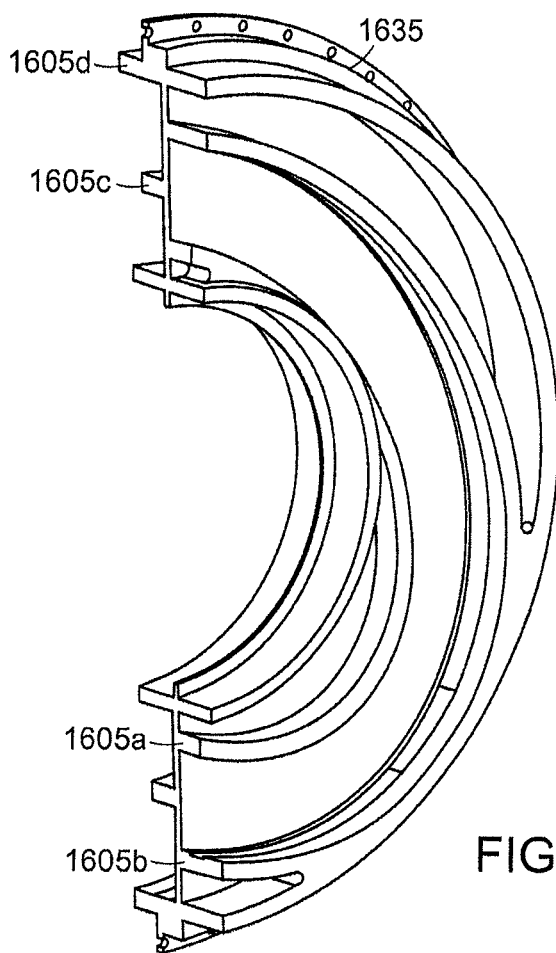


FIG. 8B

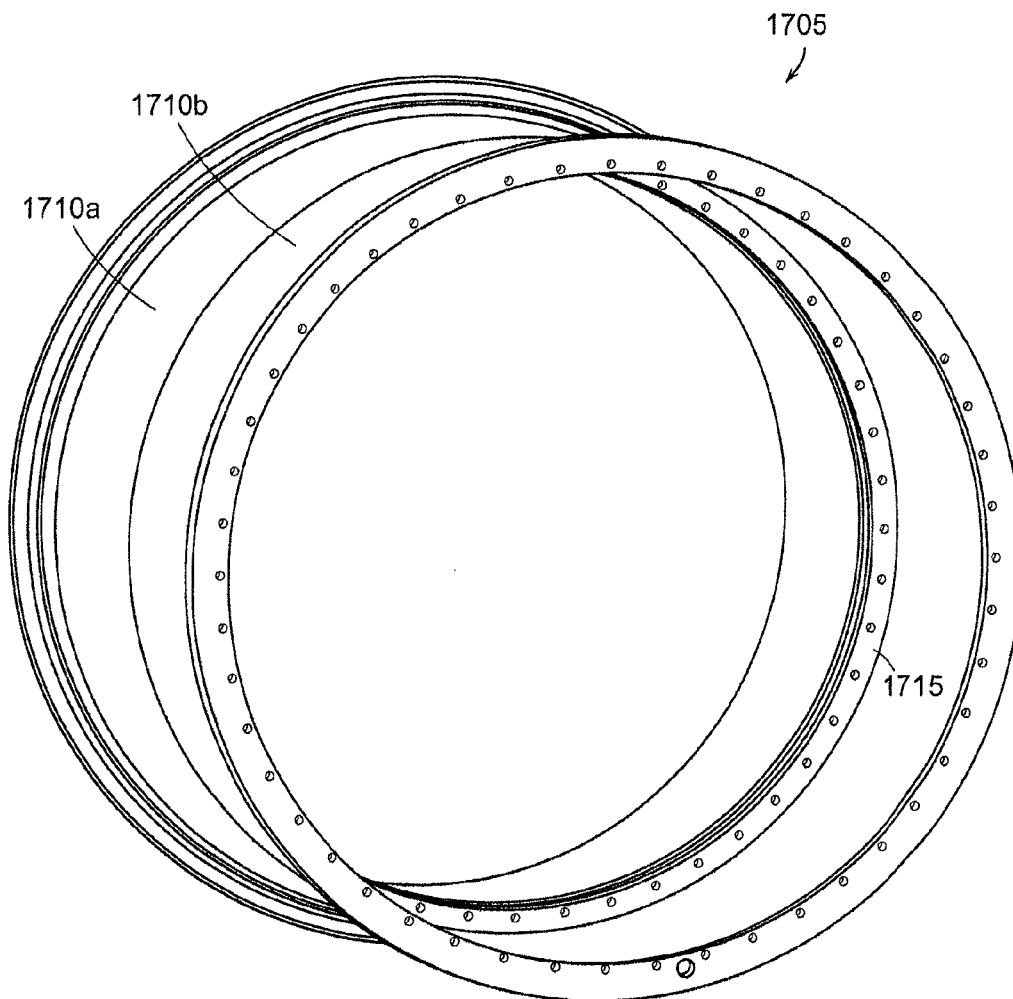


FIG. 9 A

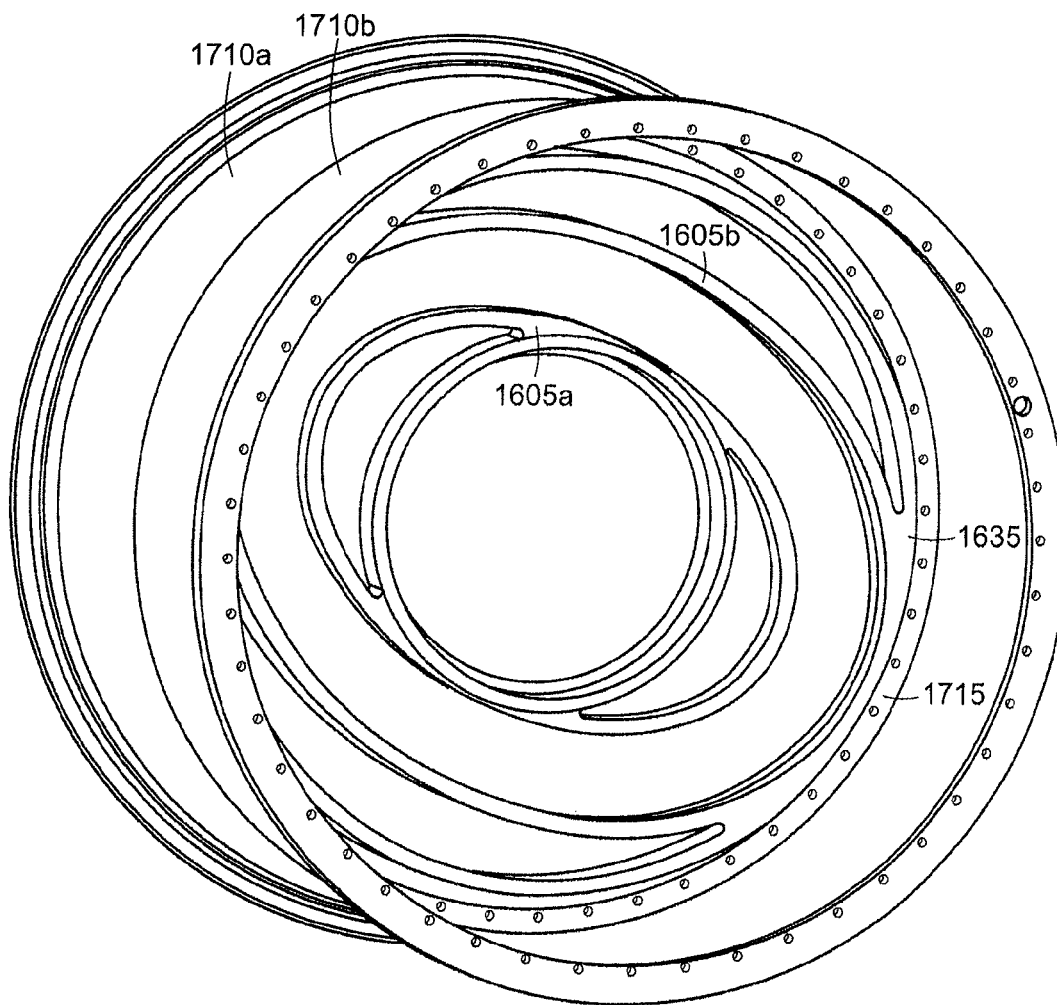


FIG. 9B

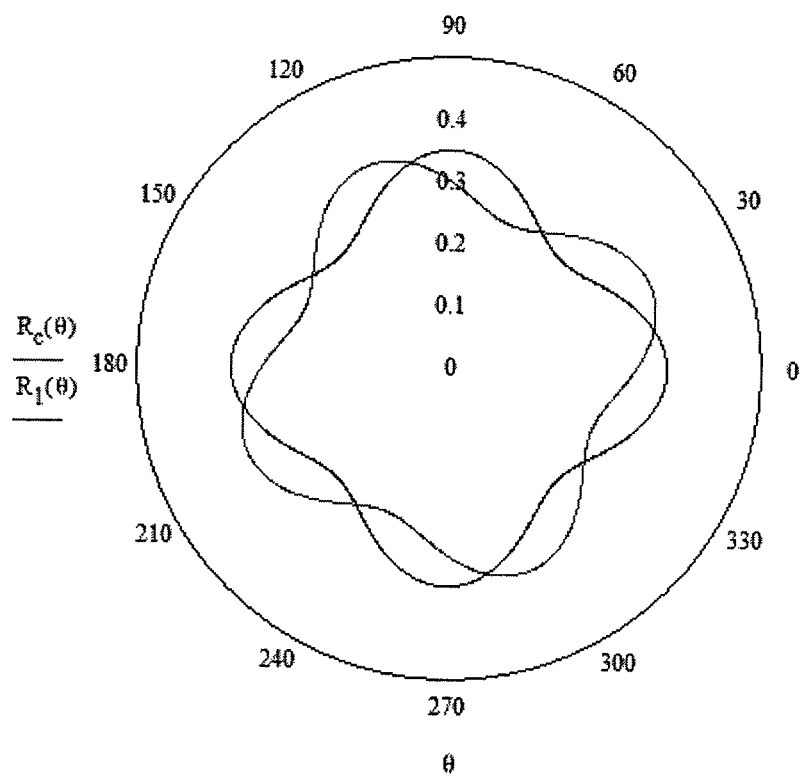


FIG. 10

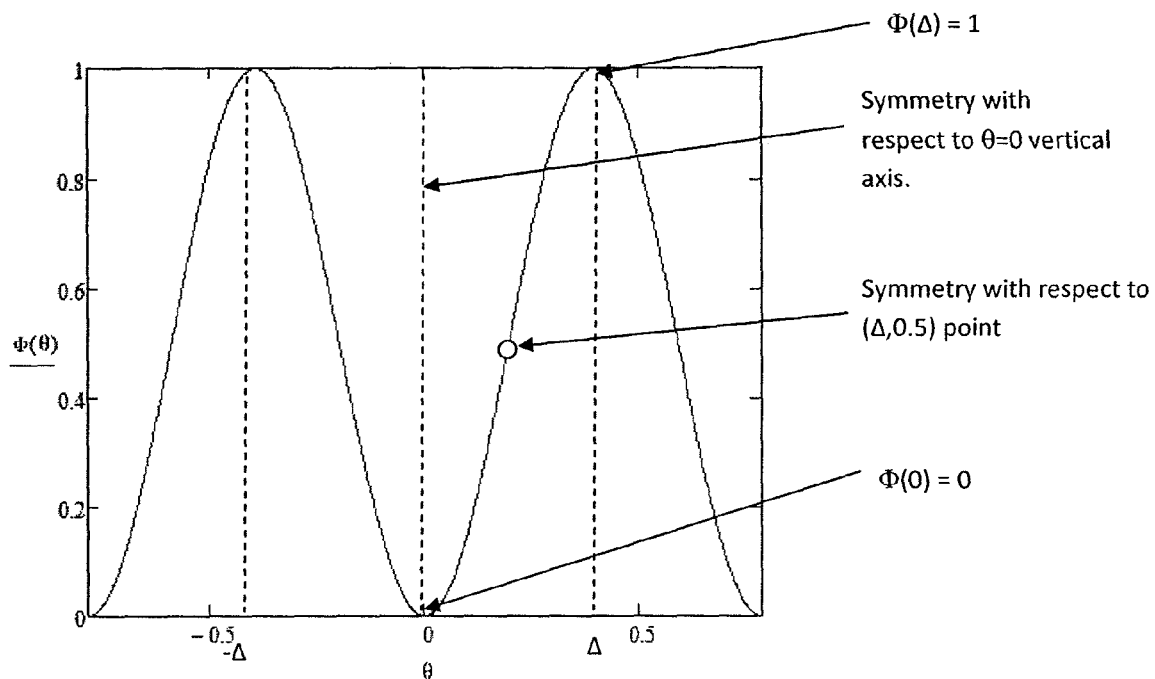


FIG. 11

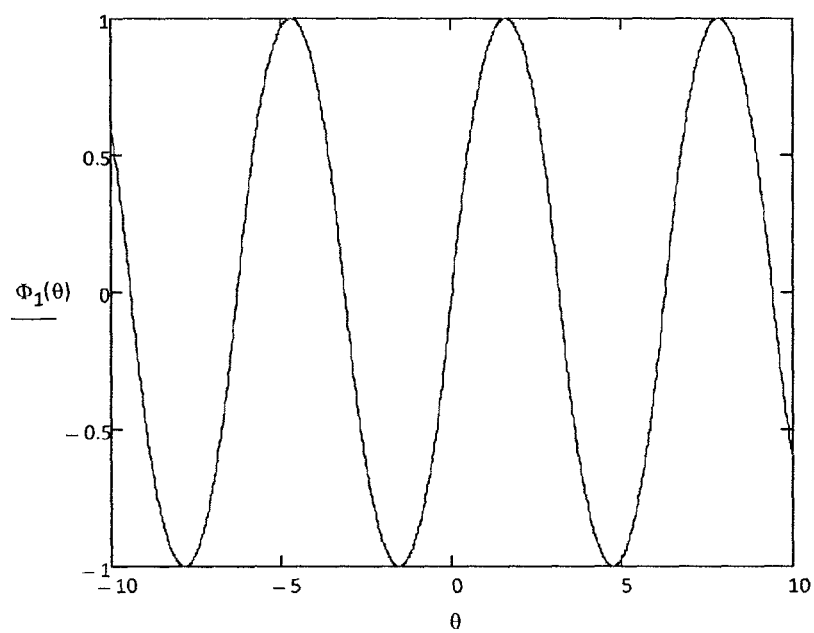


FIG. 12

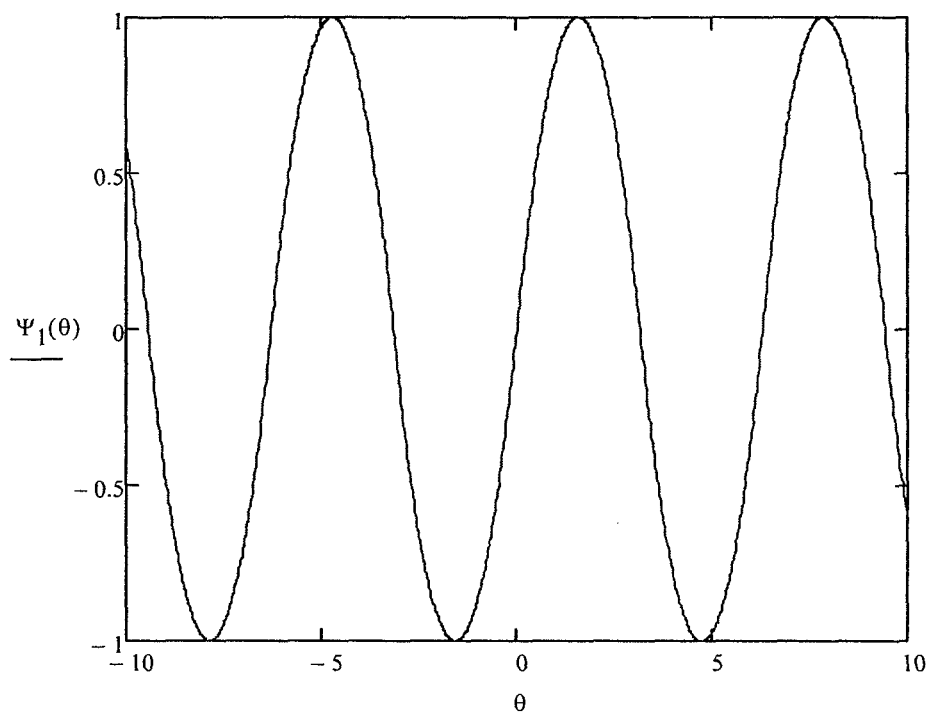


FIG. 13

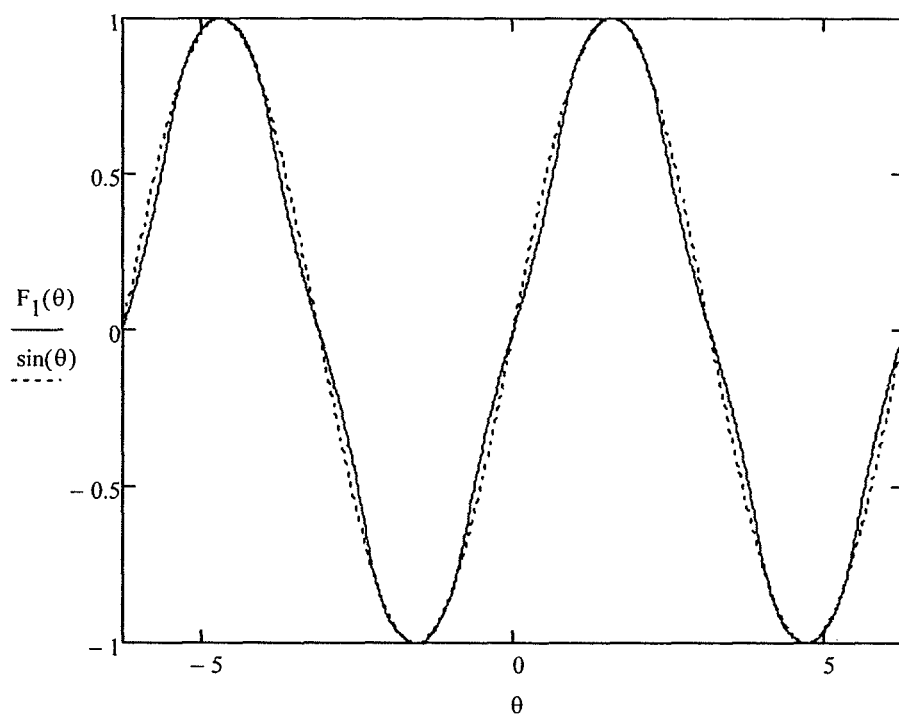


FIG. 14

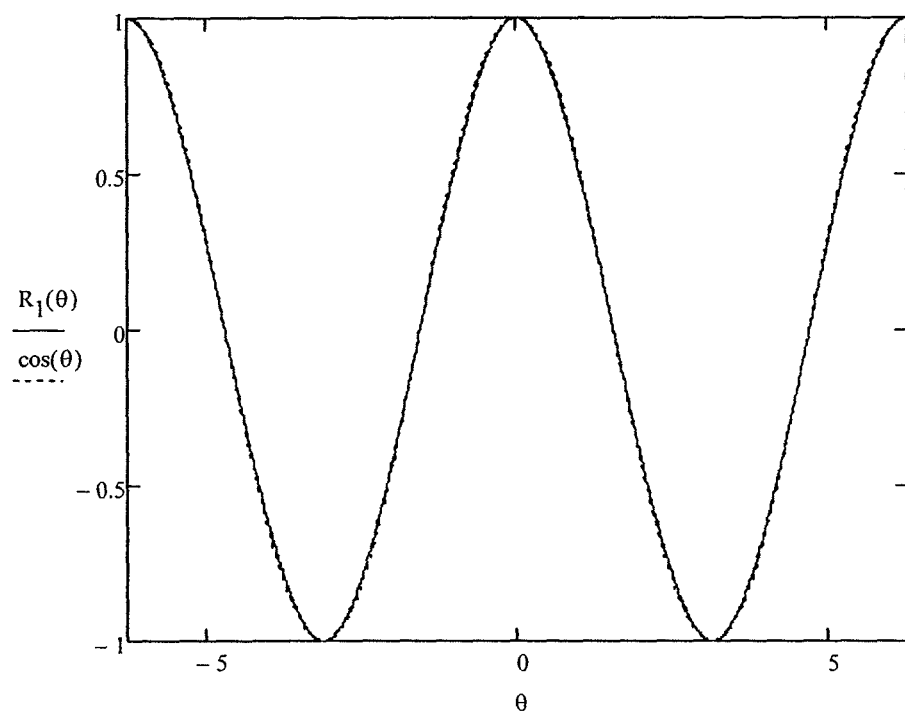


FIG. 15

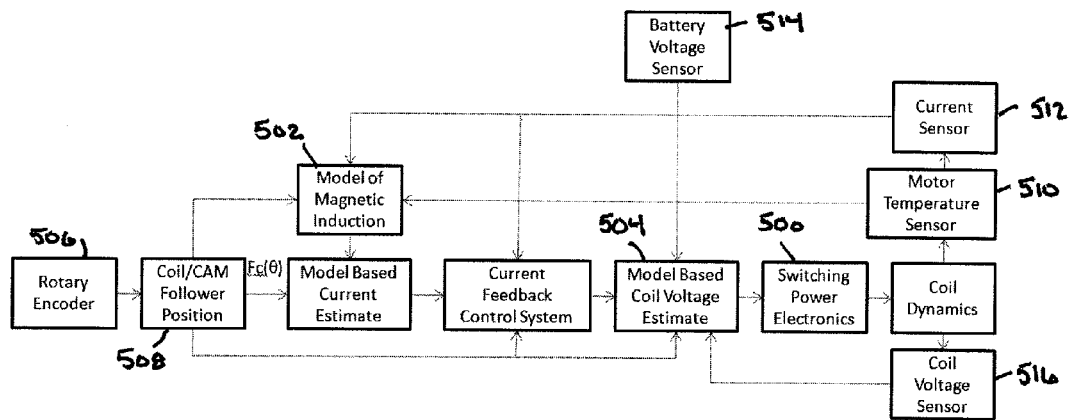


FIG. 16

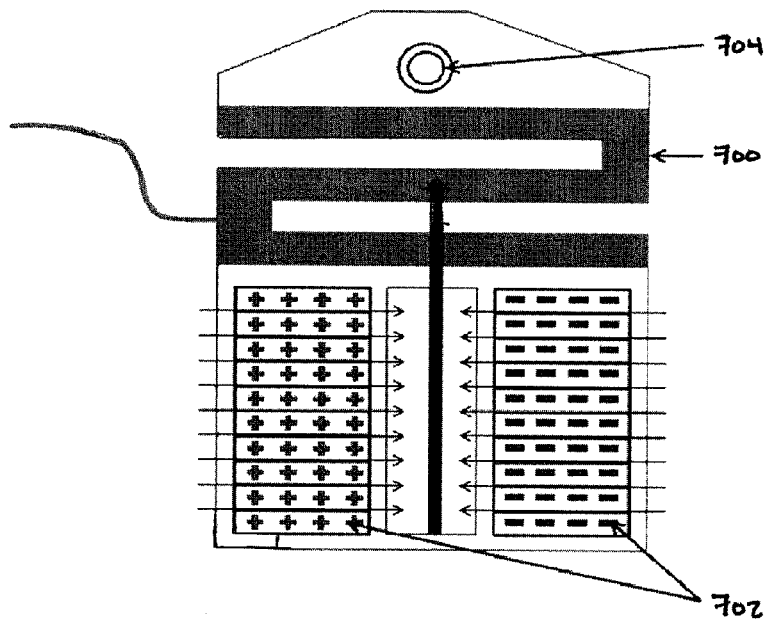


FIG. 17

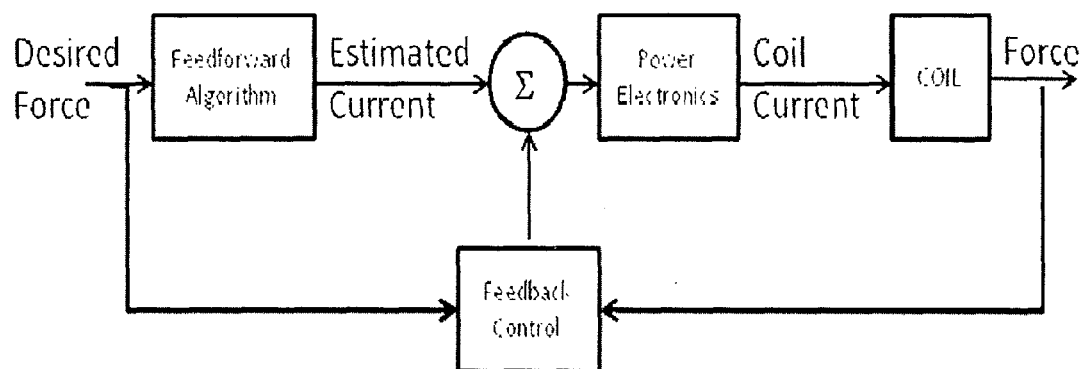


FIG. 18

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MINIMIZATION OF TORQUE RIPPLE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit or priority to U.S. Provisional Application No. 61/524,089, filed Aug. 16, 2011, the entire disclosure of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

This invention relates generally to the control of electric motors and more specifically to the control of linear Lorentz-Type actuator motors.

BACKGROUND OF THE INVENTION

Lorentz-type motors exploit the basic principle that a charged particle moving in a magnetic field experiences a force in a direction perpendicular to the direction of movement. Stated mathematically: $F=qvXB$, where F is force, q is the charge of the charged particle, v is the instantaneous velocity of the particle, and B is the magnetic field. So, if a current is flowing through a wire and a magnetic field is applied in perpendicular direction, the wire experiences a force trying to move it sideways.

A simple configuration that harnesses this principle is a coil encircling a magnetic core made of permanent magnets. The coil, referred to as the actuator, is arranged to be capable of sliding back and forth along the length of the magnetic core or magnetic stator. In that configuration, flowing a current through the coil results in a force on the coil pushing it in one direction along the length of the magnetic core. Reversing the direction of current flow causes the coil to move in the opposite direction. The magnitude of the current determines the strength of the force. And the shape of the current waveform determines how the force changes over time. With such an arrangement, by applying an appropriate current waveform to the coil, one can make the coil move back and forth along the magnetic core in a controlled manner. The controlled movement of the actuator can, in turn, be used to perform work.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A-1B illustrate a rotary motor in a wheel.
FIG. 1C illustrates a magnetic stator assembly.
FIGS. 2A-2C illustrate components of the rotary motor of FIG. 1 in various stages of motion.
FIG. 2D illustrates an exemplary shape of a cam.
FIG. 3 is a cam profile based on an Archimedes Spiral
FIG. 4 is a plot of cam radial position as a function of angle.
FIG. 5 is a sinusoidal cam profile.
FIG. 6 is a plot of cam radial position as a function of angle for the cam shown in FIG. 5.
FIGS. 7A-7B illustrate an arrangement of two hub motors for one wheel.
FIGS. 8A-8B illustrate views of two rotationally offset cams.
FIGS. 9A-9B illustrate a disc of an example rotary device coupled to a rim of a wheel.
FIG. 10 illustrate two cam profiles in quadrature.
FIG. 11 illustrate the symmetry features of a torque function.
FIG. 12 illustrates a piecewise quadratic torque function.
FIG. 13 illustrates a piecewise quadratic profile for the first derivative of the cam profile.

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FIG. 14 illustrates a non-trigonometric force function compared to a trigonometric force function.

FIG. 15 illustrates a non-trigonometric cam profile compared to a trigonometric cam profile.

FIG. 16 is an exemplary control system for providing constant torque.

FIG. 17 shows a load cell for directly measuring the Lorentz force.

FIG. 18 is an exemplary control system which employs feedback for force profile generation.

DETAILED DESCRIPTION

The subject of this application is the design and operation of a hub-mounted motor assembly so as to minimize torque ripple. The hub-mounted motor is a linear Lorentz-type actuator motor. Before discussing the design and operation of the hub-mounted motor assembly, a brief review of the linear Lorentz-type actuator motor will be presented. A more detailed discussion can be found in U.S. Ser. No. 12/590,495, entitled "Electric Motor," and incorporated herein in its entirety by reference.

The Linear Lorentz-Type Actuator Motor

The linear Lorentz-type actuator motor is a rotary device **100** that is mounted inside a wheel on a vehicle, as illustrated in FIG. 1A. Rotary device **100** includes a magnetic stator assembly **120**, opposed electromagnetic actuators **110a**, **110b**, and a linear-to-rotary converter (e.g., oval-shaped cam) **105**. Rotary device **100** is attached to the chassis of a vehicle, for example, at a point on the far side of the wheel (not shown). Rotary device **100** is attached to the wheel via cam **105** using a circular support plate, for example, which has been removed to show the inside of the wheel. Such a plate is attached to both the rim of the wheel and cam **105** using fasteners, such as bolts. The wheel and cam support plate rotate relative to a hub **145** about a bearing **150**.

FIG. 1B shows rotary device **100** from the side of the wheel **140** with the tire and some other components removed. The core of rotary device **100** includes cam **105**, two opposed electromagnetic actuators **110a**, **110b**, and a magnetic stator assembly **120**. Electromagnetic actuators **110a**, **110b** each house a coil **115a**, **115b** that encircles magnetic stator assembly **120**. Magnetic actuators **110a**, **110b** is arranged to reciprocate relative to magnetic stator assembly **120** when an appropriate drive signal is applied to coils **115a**, **115b**. One electromagnetic actuator **110a** is shown having a housing **155a** surrounding its coil **115a** and the other electromagnetic actuator **110b** is shown with its housing removed to show its coil **115b**.

Magnetic stator assembly **120** depicted in FIG. 1B is oriented vertically and includes a plurality of magnetic stators **125a**, **125b**, each of which includes multiple individual permanent magnets oriented so that their magnetic moments are perpendicular to the axis of magnetic stator assembly **120**. When current is applied to coils **115a**, **115b** of the electromagnetic actuators **110a**, **110b** (e.g., alternating current), actuators **110a**, **110b** are forced to move vertically along magnetic stator assembly **120** due to the resulting electromagnetic forces (i.e., the Lorentz forces). As is well known, when a coil carrying an electrical current is placed in a magnetic field, each of the moving charges of that current experiences what is known as the Lorentz force, and collectively they create a net force on the coil. The direction of movement and force generated is controlled by the polarity and amplitude of the current induced in the coil.

Rotary device **100** also includes a plurality of shafts **130a**, **130b**, coupled to a bearing support structure **165**. Electro-

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magnetic actuators **110a**, **110b** slide along the shafts using, for example, linear bearings. Attached to each electromagnetic actuator **110a**, **110b** is a pair of followers **135a-d** that interface with cam **105** to convert their linear motion to rotary motion of the cam. To reduce friction, followers **135a-d** freely rotate so as to roll over the surfaces of cam **105** during the operating cycle. Followers **135a-d** are attached to electromagnetic actuators **110a**, **110b** via, for example, the actuators' housings. As electromagnetic actuators **110a**, **110b** reciprocate, the force exerted by followers **135a-d** on cam **105** drives cam **105** in rotary motion.

FIG. 1C illustrates magnetic stator assembly **120** with two magnetic stators **125a**, **125b**. Magnetic stators **125a**, **125b** each include multiple magnets. For example, magnetic stator **125a** includes, on one end surface portion, eight magnets **160a-h**. All of the magnets **160** have their magnetic moments oriented perpendicular to the surface on which they are mounted and in the same direction.

FIGS. 2A-C illustrate components of rotary device **100** in action, including the rotary device's electromagnetic actuators **110a**, **110b** (with associated coils **115a**, **115b** and followers **135a-d**) and cam **105** moving relative to the magnetic stator assembly **120** (including associated magnetic stators **125a**, **125b**). The rim, the wheel, and the housings by which the followers are attached to the coils are not shown in these figures. As illustrated by FIGS. 2A-C, the reciprocal movement of the coils **115a**, **115b** in opposition drives cam **105** to rotate, which, in turn, causes a wheel attached to cam **105** to rotate. Coils **115a**, **115b** are shown in FIG. 2A as being at almost their furthest distance apart. FIG. 2B shows that as coils **115a**, **115b** move closer to each other, coils **115a**, **115b** drive cam **105** to rotate in a clockwise direction, thereby causing any attached wheel to also rotate clockwise. In the example device, the force exerted on cam **105** is caused by the outer followers **135a**, **135c** squeezing-in on cam **105**. FIG. 2C shows that coils **115a**, **115b** are even closer together causing further clockwise movement of cam **105**.

After coils **115a**, **115b** have reached their closest distance to each other and cam **105**, in this case, has rotated ninety degrees, coils **115a**, **115b** begin to move away from each other and drive cam **105** to continue to rotate clockwise. As coils **115a**, **115b** move away from each other, inner followers **135b**, **135d** exert force on cam **105** by pushing outward on cam **105**.

It is noted that cam **105** is shown in the figures as an oval shape, but it may have a more complex shape, such as, for example, a shape having an even number of lobes, as illustrated in FIG. 2D. The sides of each lobe may be shaped in the form of a sine wave, a portion of an Archimedes spiral, or some other curve, for example. The number of lobes determines how many cycles the coils must complete to cause the cam to rotate full circle. A cam with two lobes will rotate full circle upon two coil cycles. A cam with four lobes will rotate full circle upon four coil cycles. Additionally, more lobes in a cam results in a higher torque.

Analysis of Torque

The motor consists of circular disk with an outer cam and inner cam. Two cam followers linked to a coil can create a radial force on the cam. The force exerted by the cam followers in turn creates a torque on the disk.

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The idealized equation for the Torque $T_c(\theta)$ generated by the cam follower is given by the following equation:

$$T_c(\theta) = F_c(\theta) \cdot \frac{dR_c(\theta)}{d\theta} \quad \text{Eq. 1}$$

where $F_c(\theta)$ is the radial force generated by the cam follower, and $R_c(\theta)$ is the distance of the cam follower from the center of the disk. As noted above, in the motor, the force is generated from a current running in a coil and interacting with a magnetic field.

If the force is constant throughout a half stroke and the slope defining the position of the cam follower as a function of the wheel angle is also constant, that produces a torque that is constant throughout the cycle. The two dimensional shape of the cam would then be as depicted in FIG. 3.

In FIG. (1), θ is the position (rotation) of the wheel in radians and the disk has four lobes. The cam follower exerts a vertical force as indicated by the arrow. The position of the cam in polar coordinates is given by the curve shown in FIG. 4.

Although this cam profile easily lends itself to a drive signal that yields a constant torque, it presents two major drawbacks: the need to instantaneously change the coil velocity at the end of the cam motion and the need to instantaneously change the current that generates the force exerted by the cam.

The approximate equation giving the force required to accelerate and decelerate the coil is:

$$F_r = M_c \cdot \left[\frac{d^2}{dt^2} R_c(\theta) \cdot \left(\frac{d\theta}{dt} \right)^2 + \frac{d}{dt} R_c(\theta) \cdot \frac{d^2\theta}{dt^2} \right] \quad \text{Eq. 2}$$

where M_c is the mass of the coil. At the extremes of the stroke motion, the term

$$\frac{d^2 R_c(\theta)}{d\theta^2}$$

is theoretically infinite, which means in practice that the coil would undergo an unacceptably high shock due to the abrupt deceleration and acceleration.

Instantaneously changing the current also presents technical challenges, given that the current flows through a coil with a significant inductance. A linear approximation of the voltage required to change the current in the coil is given by:

$$V_c(t) = R_c \cdot I_c(t) + L_c \cdot \frac{dI(t)}{dt} + V_{emf}(t) \quad \text{Eq. 3}$$

where $V_c(t)$ is the voltage required across the coil as a function of the required change in coil current $I_c(t)$, R_c is the coil resistance, L_c is the coil inductance and $V_{emf}(t)$ is the back electromotive force generated by the coil as it moves through a changing magnetic field. Here again, given the discontinuity in the current the voltage across the coil would tend to infinity.

One partial solution is to change the cam profile such that its second derivative is finite and continuous at all points, i.e., it has a third order derivative. One example of such a cam

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profile would be a sinusoidal shape. In such a case, the cam profile would be given by the equation:

$$R_c(\theta) = R_0 + A_c \cdot \sin(n_1 \cdot \theta) \quad \text{Eq. 4}$$

where R_0 is the circle around which the cam evolves (mean position), A_c is the cam amplitude and n_1 is the number of lobes or number of strokes per revolution. The cam profile then looks like what is shown in FIG. 5. And in polar coordinates, the cam profile is shown in FIG. 6.

In this case the force to be generated by the coil is given by:

$$F_c(\theta) = \frac{T_c(\theta)}{\frac{d}{d\theta} R_c(\theta)} \quad \text{Eq. 5}$$

However, the derivative of the cam position $R_c(\theta)$ is null at the end of the strokes, hence the required force would also diverge to infinity. This remains true for any cam profile. If there is only one cam, the corollary is that it would not be self-starting if the initial position occurs when the cam follower is at the end of a stroke.

Using multiple cams such that their null points are spaced apart circumvents the problem. In the simplest example, there would be two cams on a disk, each on opposite side.

An Exemplary Embodiment

A wheel which implements this approach is shown in FIGS. 7A-B. In this case the tire of the wheel, and some other components, have been removed for clarity. There are two rotary devices **1500** and **1600**, one mounted on each side of a central disc **1635**. The rotary devices are similar to the rotary devices described above. Rotary device **1500** includes a pair of electromagnetic actuators **1510a**, **1510b**, and a magnetic stator assembly **1520**. Similarly, rotary device **1600** includes a pair of electromagnetic actuators **1610a**, **1610b**, and a magnetic stator assembly **1620**. Each of magnetic stator assemblies **1520**, **1620** includes two magnetic stators **1515a**, **1515b**, **1615a**, **1615b**, which include magnetic flux return paths **1640a-d** and magnets (e.g., **1630a**, **1630b**). The housings surrounding the coils of the electromagnetic actuators **1510a**, **1510b**, **1610a**, **1610b** are not shown. Each coil reciprocates along four arrays of magnets, which, as described above, may include multiple magnets. Two of the magnet arrays are located inside the coil (e.g., inner magnetic stator component **1630b**) and two are located outside the coil (e.g., outer magnetic stator component **1630a**). Each set of magnets are mounted to a magnetic flux return path **1640a-d**.

The disc **1635** includes two cams, one on either side of the disc **1635**. In this example, each cam of the device is in the form of a grove that includes an inner surface **1605a** and an outer surface **1605b**. Coupled to electromagnetic actuators **1510a** and **1510b** are two pairs of followers **1625a**, **1625b**, the different followers of each pair interfacing with a respective surface **1605a**, **1605b** of the cam. Electromagnetic actuators **1610a** and **1610b** are similarly coupled to followers. As the coils move towards each other, one of the followers of each electromagnetic actuator **1510a**, **1510b** exerts force on the inner surface **1605a** of the cam. As the coils move away from each other, the other follower exerts force on the outer surface **1605b** of the cam.

FIG. 7B illustrates a different view of the rotary devices. It should be apparent that each pair of electromagnetic actuators (pair **1510a**, **1510b** and pair **1610a**, **1610b**) are at different phases of reciprocation. This is because, in the example

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device, the cams on either side of the disc **1635** are rotationally offset from each other by, for example, forty-five degrees. This helps to prevent the actuators from stopping at a point on the cams from which it would be difficult to again start. Thus, if one pair of actuators stops on a “dead-spot” of its respective cam, the other pair of actuators would not be at a dead-spot. FIG. 7B also illustrates an arrangement of the coils and magnetic stator components. For example, magnetic stators components **1630b** and **1630c** are located inside the coil of actuator **1610a**, and magnetic stators components **1630a** and **1630d** are located outside the coil.

FIG. 8A illustrates two rotationally offset cams **1505**, **1606**. The cams **1505**, **1606** are part of or are mounted on a disc **1635**. One cam **1505** is on one side of the disc **1635**, and the other cam **1606** is on the opposite side, as indicated by the dashed line. In some devices the cam may be offset by forty-five degrees, for example. The cams **1505**, **1606** have an even number of lobes, e.g. 2, 4, 6 etc. Cams having two lobes are offset by 45 degrees. Cams having four lobes are offset by 22.5 degrees.

FIG. 8B illustrates a vertical cross-section of a disc **1635** with two rotationally offset cams, each having an inner surface **1605a**, **1605c** and an outer surface **1605b**, **1605d**. Due to the offset, the inner surfaces **1605a**, **1605c** are not in line with each other. Likewise, the outer surfaces **1605b**, **1605d** are also not in line with each other.

FIG. 9A illustrates how the disc **1635** of the example rotary device is coupled to the rim **1705** of a wheel. The rim **1705** consists of one piece to which the disc **1635** is affixed using fasteners, such as bolts, along an inner ring **1715**. Alternatively, the rim **1705** may include two parts **1710a**, **1710b** that bolt together along ring **1715**. When fastened together, the two parts **1710a**, **1710b** form a full rim **1705** with inner ring **1715**. A tire is then be mounted to the rim **1705**. FIG. 9B shows how the disc **1635** is fastened to the inner ring **1715** of the disc **1635**.

Minimizing Torque Ripple

Returning to the description of the technique for minimizing torque ripple, we direct the reader's attention to an example using two four lobe cams, which is illustrated in FIG. 10.

Note that the profiles are not mirror images but are in quadrature and that they consist of the same basic profile $R_c(x)$ but “shifted” with respect to each other. Assuming that n_c is the number of lobes in the cam, i.e. the number of times that a basic function $R_c(x)$ is repeated within one full circle, and that the derivative of the cam profile is given by $\Psi_c(n_c \cdot \theta)$, the equation for the torque provided by the summation of the torques $\Phi(\theta)$ of the individual cams would be:

$$T = \Phi(n_c \cdot \theta) + \Phi(n_c \cdot \theta + \Delta) \quad \text{Eq. 6}$$

$$T = F_c(n_c \cdot \theta) \cdot \Psi_c(n_c \cdot \theta) + F_c(n_c \cdot \theta + \Delta) \cdot \Psi_c(n_c \cdot \theta + \Delta) \quad \text{Eq. 7}$$

And typically Δ corresponds to one quarter of a lobe, i.e.

$$\Delta = \frac{\pi}{2}.$$

This leads to the following question: what is the family of functions $\Phi(\theta) = F_c(\theta) \cdot \Psi_c(\theta)$ such that total torque is constant (i.e., ripple free) when at least two out-of-phase cams and actuators are used. This equation implies that the function $\Phi(\theta)$ has a periodicity of $2 \cdot \Delta$:

$$\Phi(\theta) = T - \Phi(\theta + \Delta) \quad \text{Eq. 8}$$

$$\Phi(\theta + \Delta) = T - \Phi(\theta + 2 \cdot \Delta) \quad \text{Eq. 9}$$

Substituting:

$$\Phi(\theta) = T - (T - \Phi(\theta + 2\Delta)) = \Phi(\theta + 2\Delta) \quad \text{Eq. 10}$$

Which is as required, i.e. the function $\Phi(\theta)$ is periodic, with a period that is double that of the period of one full cam cycle. This still leaves the ensemble of functions quite large. For reasons of symmetry, it is reasonable to require that:

$$\Phi(\theta) = \Phi(-\theta) \quad \text{Eq. 11}$$

And we can also assume that the cam reaches its extremum at $\theta=0$ and $\theta=\Delta$. Hence, the class of functions $\Phi(\theta)$ that we are seeking has the following properties:

1. $\Phi(0)=0$
2. $\Phi(\Delta)=T_{\max}$ where T_{\max} is the maximum torque
3. $\Phi(\theta)$ is symmetrical with respect to the $\theta=0$ vertical axis
4. $\Phi(\theta)$ is symmetrical with respect to the point $(\Delta/2, T_{\max}/2)$.
5. $\Phi(\theta)$ is continuous.

The general shape of this function is given in FIG. 11.

We also know that the function $\Phi(\theta)$ is the product of two other functions, $F_c(\theta)$ and $\Psi(\theta)$, where $\Psi(\theta)$ must have a first order derivative, such that the cam profile given by:

$$R_c(\theta) = f(\Psi(\theta)) \quad \text{Eq. 12}$$

Intuitively it would also be desirable that the functions $F_c(\theta)$, $R_c(\theta)$ and $\Psi(\theta)$ have the same symmetry. Therefore one reasonable question to ask is would there be a function such that $F_c(\theta)$ and $\Psi(\theta)$ are the same function? In this case:

$$T = \Psi^2(n_c \cdot \theta) + \Psi^2(n_c \cdot \theta + \Delta) \quad \text{Eq. 13}$$

which is the basic equation of a right triangle.

Here the components in quadrature can be viewed as the sides of a right triangle, such that one is a sine of an angle and the other one the cosine of the angle:

$$\cos^2(\varphi) = \Psi^2(n_c \cdot \theta) \quad \text{Eq. 14}$$

$$\begin{aligned} \cos(\varphi + \Delta) &= \cos(\varphi + \frac{\pi}{2}) \\ &= \cos(\varphi)\cos(\frac{\pi}{2}) - \sin(\varphi)\sin(\frac{\pi}{2}) \\ &= -\sin(\varphi) \end{aligned} \quad \text{Eq. 15}$$

$$\therefore \cos^2(\varphi + \Delta) = \sin^2(\varphi) \quad \text{Eq. 16}$$

In conclusion, if the shape of the cam is a sine function, its derivative is a cosine function, its derivative is a sine function, and if the current waveform is also a sine function then the two components in quadrature sum up to a constant torque with no ripple.

In principle, there is an infinite number of functions $F_c(\theta)$, $R_c(\theta)$ and $\Psi(\theta)$ leading to a constant torque. In practice, the choice is rather limited, given that we must have:

$$F_c(\theta) = \frac{\Phi(\theta)}{\Psi(\theta)} \quad \text{Eq. 17}$$

And when both $\Phi(\theta)$ and $\Psi(\theta)$ tend to zero, the ratio must also converge to zero. We also require to a first order derivative. It becomes a non-trivial exercise to find other functions besides the sinusoidal type function to meet these criteria, and they typically end up very close to a trigonometric function. However, in the modern day of microprocessor based digital control where computation time is a prime consideration such alternate functions might have a benefit.

One of the simplest examples of an alternate approach would be to use piece-wise quadratic functions for $\Phi_1(\theta)$ and $\Psi_1(\theta)$, as given in this MathCAD recursive representation, omitting for the time being the number of lobes in the equations:

$$\Phi_1(\theta) := \begin{cases} z \leftarrow |\theta| \\ z \leftarrow \text{mod}(z, \pi) \\ y \leftarrow \frac{8}{\pi^2} \cdot z^2 \text{ if } z \leq \frac{\pi}{4} \\ \text{otherwise} \\ \left| \begin{array}{l} y \leftarrow 1 - \Phi_1(\frac{\pi}{2} - z) \text{ if } z \leq \frac{\pi}{2} \\ y \leftarrow \Phi_1(\pi - z) \text{ otherwise} \end{array} \right. \\ y \leftarrow y \end{cases} \quad \text{Eq. (18)}$$

where $\Phi_1(\theta)$ is shown in FIG. 12.

$$\Psi_1(x) := \begin{cases} z \leftarrow |x| \\ z \leftarrow \text{mod}(z, 2\pi) \\ y \leftarrow 1 - \frac{4}{\pi^2} \cdot (\frac{\pi}{2} - z)^2 \text{ if } z \leq \frac{\pi}{2} \\ \text{otherwise} \\ \left| \begin{array}{l} y \leftarrow \Psi_1(\pi - z) \text{ if } z \leq \pi \\ y \leftarrow -\Psi_1(z - \pi) \text{ otherwise} \end{array} \right. \\ y \leftarrow y \cdot \text{sign}(x) \end{cases} \quad \text{Eq. (19)}$$

where $\Psi_1(\theta)$ is shown in FIG. 13.

The resulting force profile F_1 calculated from the ratio of Φ_1 to Ψ_1 is outlined in FIG. 14, and compared to a trigonometric function.

Finally, the CAM profile R_1 is computed from the integral of Ψ_1 and compared to a trigonometric function in FIG. 15.

Although difficult to prove, it is to be expected that all CAM shapes and force profiles that are well behaved in terms of symmetry and smoothness would all be very close in shape to trigonometric functions. Only two CAMs in quadrature were analyzed here, the same approach could be used for other even numbers of CAMs.

In actual practice, although it is easy to generate a CAM with a precise triangular function, it is more difficult to generate a force profile that is a sinusoidal. For an idealized Lorentz force actuator assuming a constant magnetic induction B, this would translate in generating an exact current profile with a sinusoidal function. However, in practice the magnetic induction B is not constant and depends on the geometry of the permanent magnets used to generate the field. Furthermore, the field generated by magnets depends on the temperature and is also influenced by the current flowing in the motor coil. All of these effects must be carefully modeled to generate a current that truly minimizes ripple.

A typical control system is depicted in FIG. 16. It includes switching power electronics 500 which supplies a pulse width modulated drive signal to the coils in the motor to produce the desired torque and speed. The operation of switching power electronics 500 is controlled based on models of the motor including a model 502 of the magnetic induction of the motor (i.e., the magnetic field seen by the coil as a function of the position of the coil, the current in the coil, and the temperature of the coil) and a model 504 which enables one to determine the voltage of a pulse width modulated signal that is necessary to produce the desired drive current in the coils. Input for the models comes from a rotary encoder 506 which indicates the

angular position of the cam or wheel, a conversion module **508** that converts the angular position into a position of the coil or cam follower, and various sensors in the motor supplying information about the motor's operating conditions. Note that the model changes depending on operating conditions and some the model needs to take these into account. The various sensors include a motor temperature sensor **510**, a current sensor **512**, a battery voltage sensor **514**, and a coil voltage sensor **516**.

From a wheel rotary encoder **506**, the angular and radial position of the coil and cam follower are calculated. From the cam follower position, the desired force to be generated by the coil is calculated from a function $F_c(\theta)$. The desired current required to produce this force is equal to the current in the coil times the magnetic induction. Since the magnetic induction B is not exactly uniform, it has to be estimated from model **502** using the motor temperature, coil current, and relative position of the coil with respect to the permanent magnets.

The desired current is converted to a pulse modulation width. This is done in two steps. First from the model of the coil dynamics, a voltage required across the coil to obtain the desired current in the coil is calculated. Then, a model of the power electronics is required to calculate the switching duty cycle based on the desired voltage, the supply voltage, the actual current in the coil and the voltage across the coil.

So far the control is all feed forward model based. However, the models have a certain level of inaccuracy, so feedback is used to correct between the desired current and measured current.

An alternative approach to generating the desired force profile is by measuring the force that is generated and directly controlling that force using a feedback control on current, as summarized in FIGS. **17** and **18**.

FIG. **17** illustrates how the Lorentz force generated by the coil can be directly measured. A load cell **700** is inserted between the coil **702** and the cam follower **704**. The cam follower itself can be subject to large off-axis forces from the reaction with the cam. However, force transducers can be designed to be largely insensitive to such lateral forces. Therefore, an accurate measurement of the axial force can be obtained from the load cell and then used in various control algorithms to adjust the current such that the required force profile is generated.

FIG. **18** illustrates one of the many alternative control strategies that can be used to obtain the required force profile. The algorithms described above to estimate the current needed to get the desired force could be used in a feedforward manner. Then, the error between the desired force and measured coil force would be feed to some other feedback control system which uses that measurement to make current corrections in order to obtain the desired force profile. The advantage of the feedback control approach is that it will tend to be more stable than a purely feed forward approach.

Other embodiments are within the following claims.

What is claimed is:

1. An electric motor comprising:

a first linear actuator including a first coil;
a second linear actuator including a second coil;
a rotational shaft;

a cam assembly mounted on said rotational shaft for translating linear movement of the first and second linear actuators to rotational movement of the rotational shaft; and

a controller programmed to generate during operation a first drive signal for the first coil and a second drive signal for the second coil, wherein the first drive signal causes the first linear actuator through interacting with

the cam assembly to generate a first torque on the rotational shaft that varies periodically over a complete rotation of the shaft and the second drive signal causes the second linear actuator through interacting with the cam assembly to generate a second torque on the rotational shaft that varies periodically over the complete rotation of the shaft,

wherein the controller is programmed to generate the first and second drive signals to produce a total torque that is substantially ripple free constant throughout the complete rotation of the shaft, the total torque comprising a sum of the first torque and the second torque.

2. The electric motor of claim **1**, further comprising:

a first cam follower assembly coupling the first linear actuator to the cam assembly; and

a second cam follower assembly coupling the second linear actuator to the cam assembly,

wherein the first cam follower assembly is arranged to ride along a first cam surface within the cam assembly, said first cam surface having a first profile over 360 degrees of rotation,

wherein the second cam follower assembly is arranged to ride along a second cam surface within the cam assembly, said second cam surface having a second profile over 360 degrees of rotation, and

wherein the first and second profiles as well as the first and second drive signals are selected to generate the substantially ripple free torque.

3. The electric motor of claim **2**, wherein the first profile is described by n cycles of a trigonometric function, wherein n is an even integer.

4. The electric motor of claim **3**, wherein the second profile is described by n cycles of said trigonometric function.

5. The electric motor of claim **4**, wherein n equals 4.

6. The electric motor of claim **5**, wherein said trigonometric function is a sine function.

7. The electric motor of claim **6**, wherein the first profile is shifted in phase relative to the second profile by

$$\frac{\pi}{2n}$$

radians.

8. The electric motor of claim **2**, wherein the first profile follows a curve that is continuous over 360 degrees and that has a first derivative that is continuous over 360 degrees.

9. The electric motor of claim **2**, wherein each of the first and second profiles has a period of

$$\frac{360}{n}$$

degrees and each of the first and second torques has a period of

$$\frac{180}{n}$$

degrees, and wherein n is an even integer.

10. The electric motor of claim **9** wherein n equals 4.

11. The electric motor of claim **6**, wherein the first and second profiles are aligned in phase and wherein the first and

second linear actuators are shifted in orientation relative to each other by

$$\frac{\pi}{2n}$$

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radians.

12. The electric motor of claim 2, wherein the first and second cam surfaces are separate surfaces. 10

13. The electric motor of claim 2, wherein the first and second cam surfaces are the same surface.

14. The electric motor of claim 2, wherein:

a first derivative of the first profile is represented by $\psi(n_c \cdot \theta)$; 15

a first derivative of the second profile is represented by $\psi(n_c \cdot \theta + \Delta)$;

a force generated by the first actuator is represented by $F_c(n_c \cdot \theta)$;

a force generated by the second actuator is represented by $F_c(n_c \cdot \theta + \Delta)$; and 20

wherein θ is an angle of rotation of the shaft, n_c is an even integer representing a number of cycles of the first and second profiles over a complete rotation of the shaft, Δ is a phase shift between the first and second profiles, and 25
wherein $F_c(n_c \cdot \theta) \cdot \Psi(n_c \cdot \theta) + F_c(n_c \cdot \theta + \Delta) \cdot \Psi(n_c \cdot \theta + \Delta)$ is constant as a function of θ .

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